High-magnification, high-speed PIV for near-wall boundary layer studies

C. Willert, J. Klinner
DLR Institute of Propulsion Technology, Köln (GERMANY)

Outline

- “Profile PIV” Measurement principle
- Some highlights of recent applications
  - EuHIT Project “Large Scale Structures”, LML, May 2015
  - EuHIT Project “HoloPipe”, CICLoPE, Forli, May 2016

Basic measurement setup

Highspeed camera with lens

- Photron SA5, 1024x1024 @ 7kHz
- Zeiss Makro Planar, 100mm/$f_{\#}2$

CW Laser

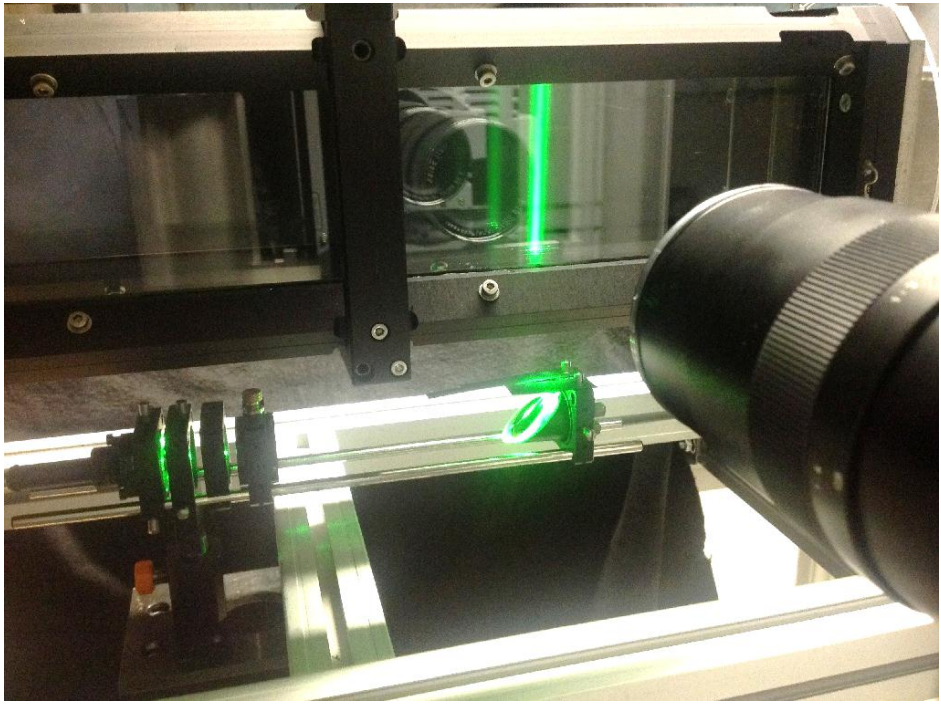
- Coherent Verdi, P_{max}= 5W

Light sheet optics + mirror

- 1 cylinder lens (-25mm)
- 1 spherical lens (200mm)

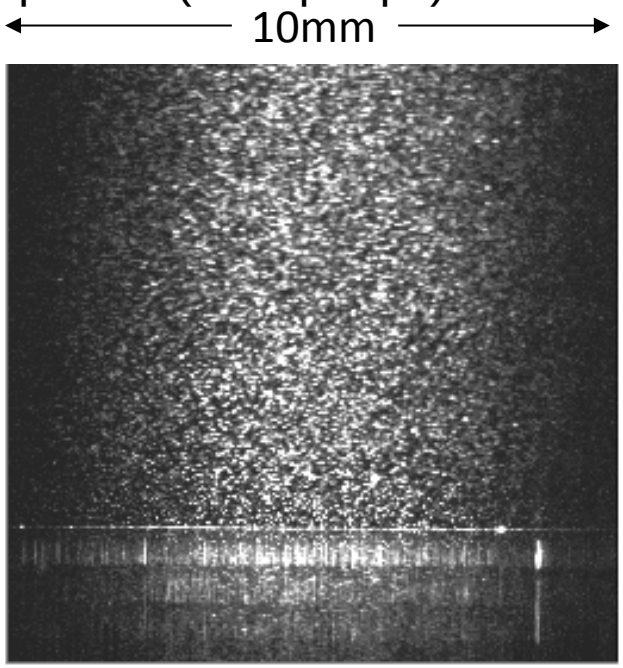
Seeding

- 1µm parafin oil droplets from Laskin seeder with impactor

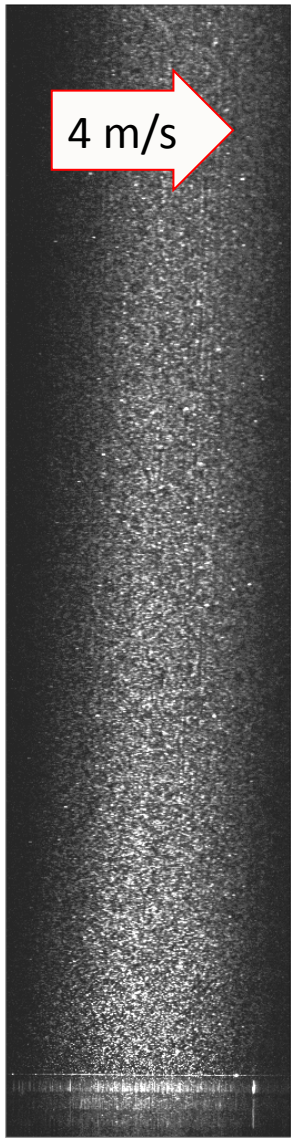


Sample image data

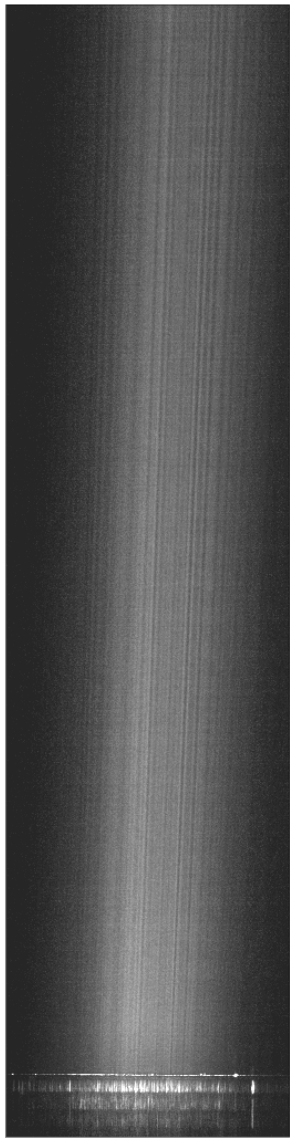
- laser power: *P* ~ 3W
- frame rate: 20 kHz
- shutter: 25 µs
- resolution: 256 ×1024 pixel
- depth: 8 bit/pixel (TIFF)
- signal: ~50 counts
- *m* = 25.27 px/mm (39.6 µm/px)



Single image



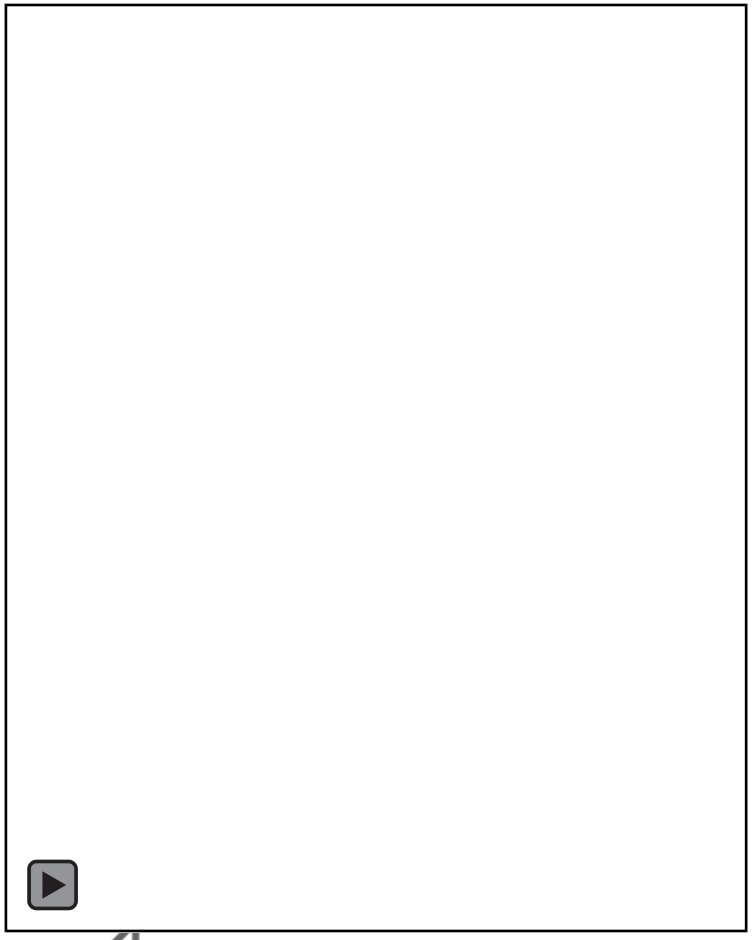
Mean

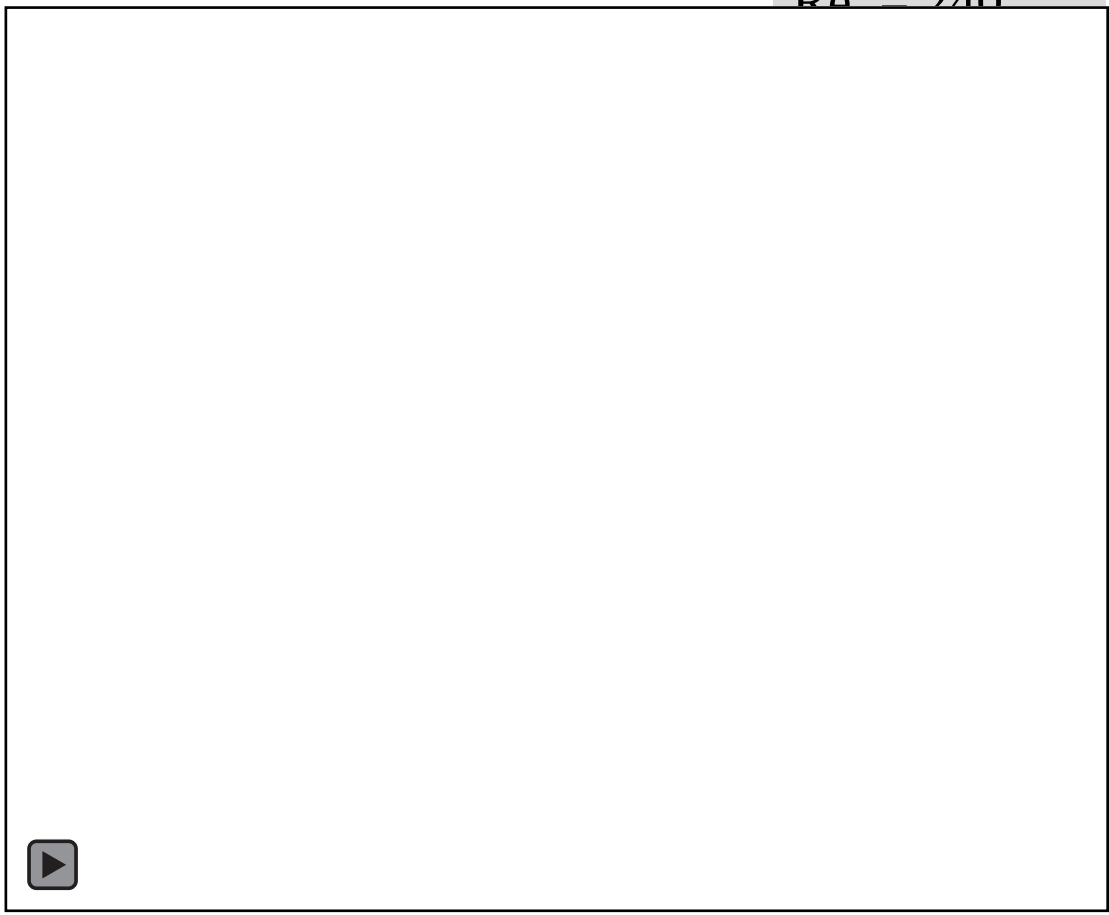


Time resolved PIV of boundary layer* at 20 kHz

*) square channel of 76 x 76 mm^2

$Re_\delta = 4800$
$Re_\theta = 520$
$Re_\tau = 240$





Multi-PIV Measurements of an Adverse Pressure Gradient Turbulent Boundary Layer

C. Kähler, S. Scharnowski, R. Hain
Institut für Fluidmechanik u. Aerodynamik, Uni.BW München

C. Willert, J. Klinner
DLR Institut für Antriebstechnik, Köln

A. Schröder, J. Agocs, R. Geisler, A. Röse
DLR Institut für Aerodynamik und Strömungstechnik, Göttingen

J. Soria, C. Atkinson, O. Amili
Monash University, Melbourne

M. Stanislas, J.M. Foucaut, C. Cuvier, S. Srinath, J.P. Laval
Laboratoire de Mécanique de Lille, CNRS

EuHIT

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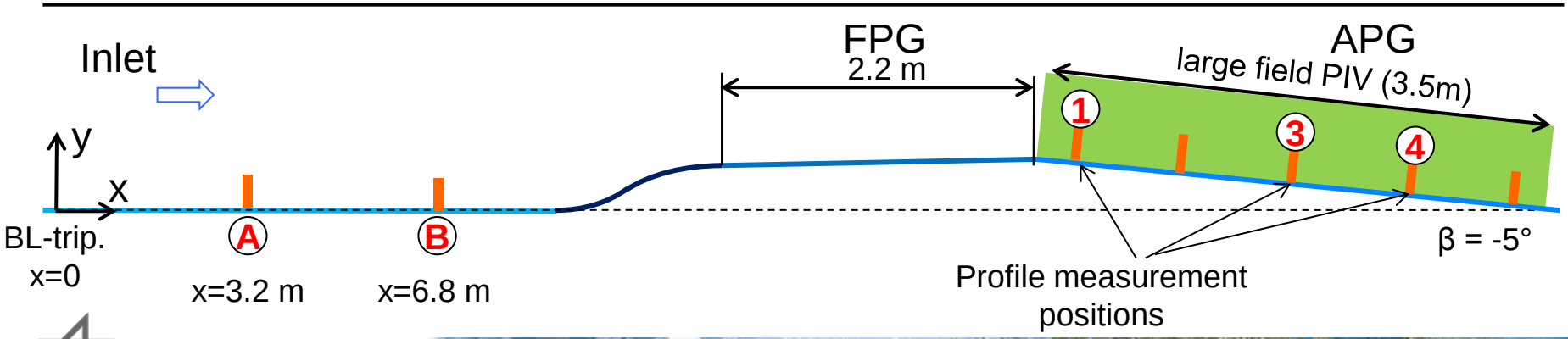
Large Scale Structure under Adverse Pressure Gradient

Facility: LML Boundary Layer Wind Tunnel (LML), France

Partners

- LML-Lille
- UniBW-München
- DLR (Gö/KP)
- Monash University



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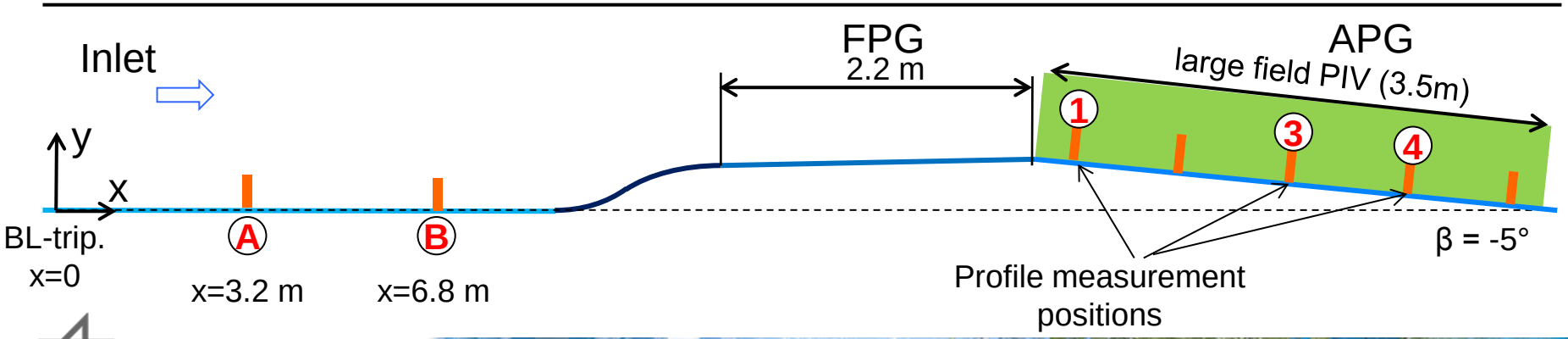
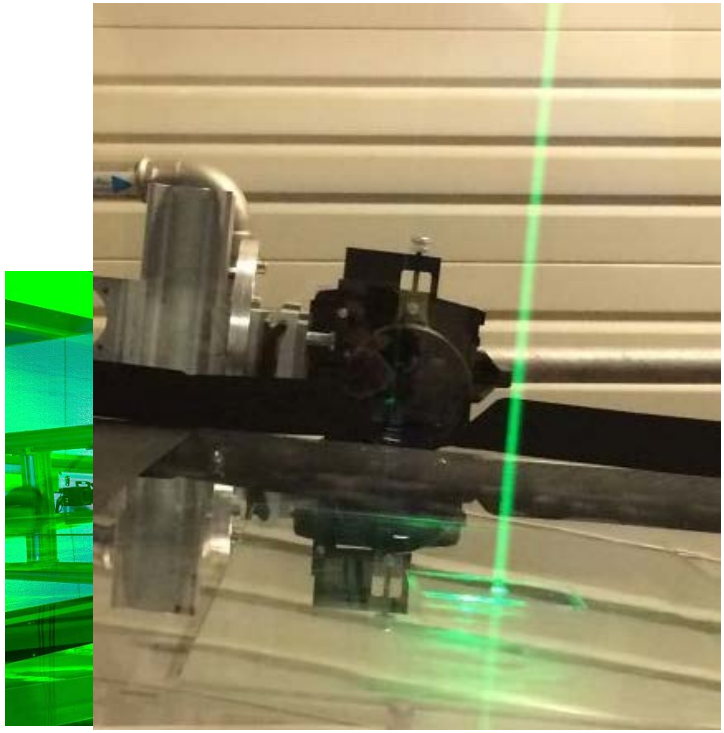
PIV Measurement methods utilized

- **2C 2D PIV** to capture entire APG region (3.5m) using 16 cameras
- 3C 2D PIV (Stereo) of selected spanwise positions in APG (and upstream)
- **High-speed 2C 2D PIV** to measure near wall characteristics (wall shear stress) at selected positions
- 2D wall shear measurements based on shear film
- Long-range microscopy to measure wall shear stress



High-speed 2C-2D PIV



→ wall-shear stress and near wall statistics

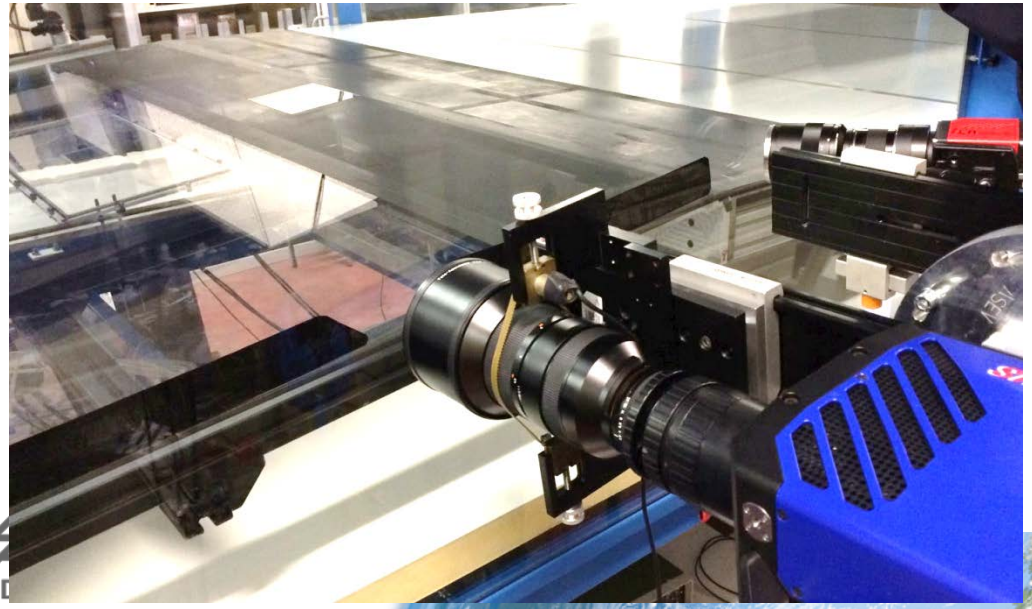
~ 1m working distance

(Zeiss ApoTessar 300mm/2.8 lens)

→ m = 0.44 (~25 µm/Pixel) → (> 1y^+ / Pixel)

Camera: PCO Dimax-S4, 36GB

→ up 503,000 images per run (178x288 pixels)

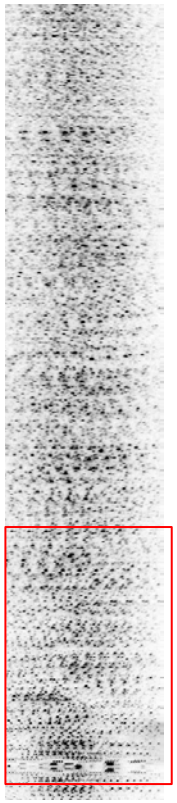


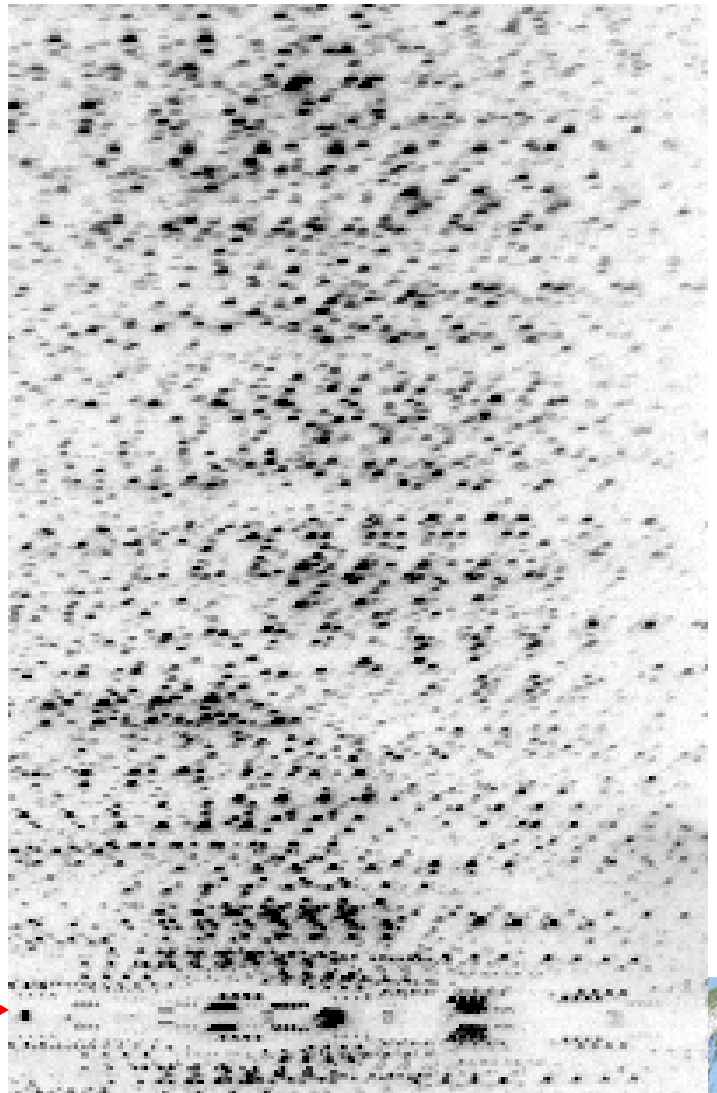
Position A – Upstream of model, U_∞ = 5 m/s

6.7 kHz acquisition rate (Δt = 150µs) 125,000 images (~19 s)

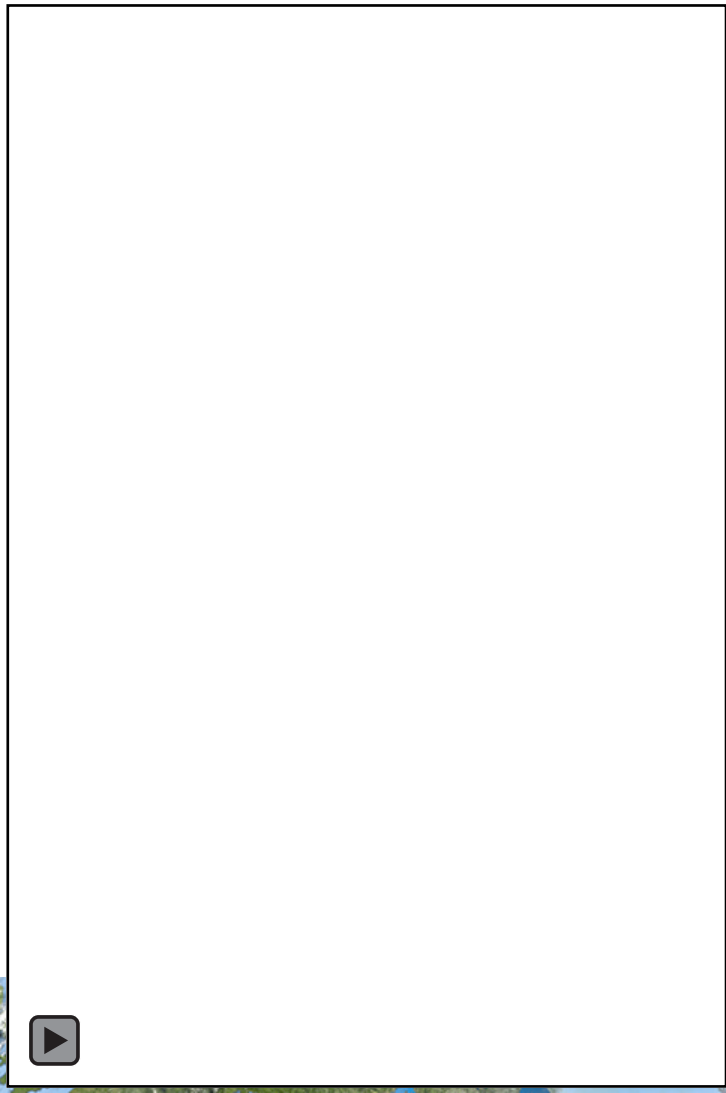
200px
(5mm)

1008 pixel (25mm)

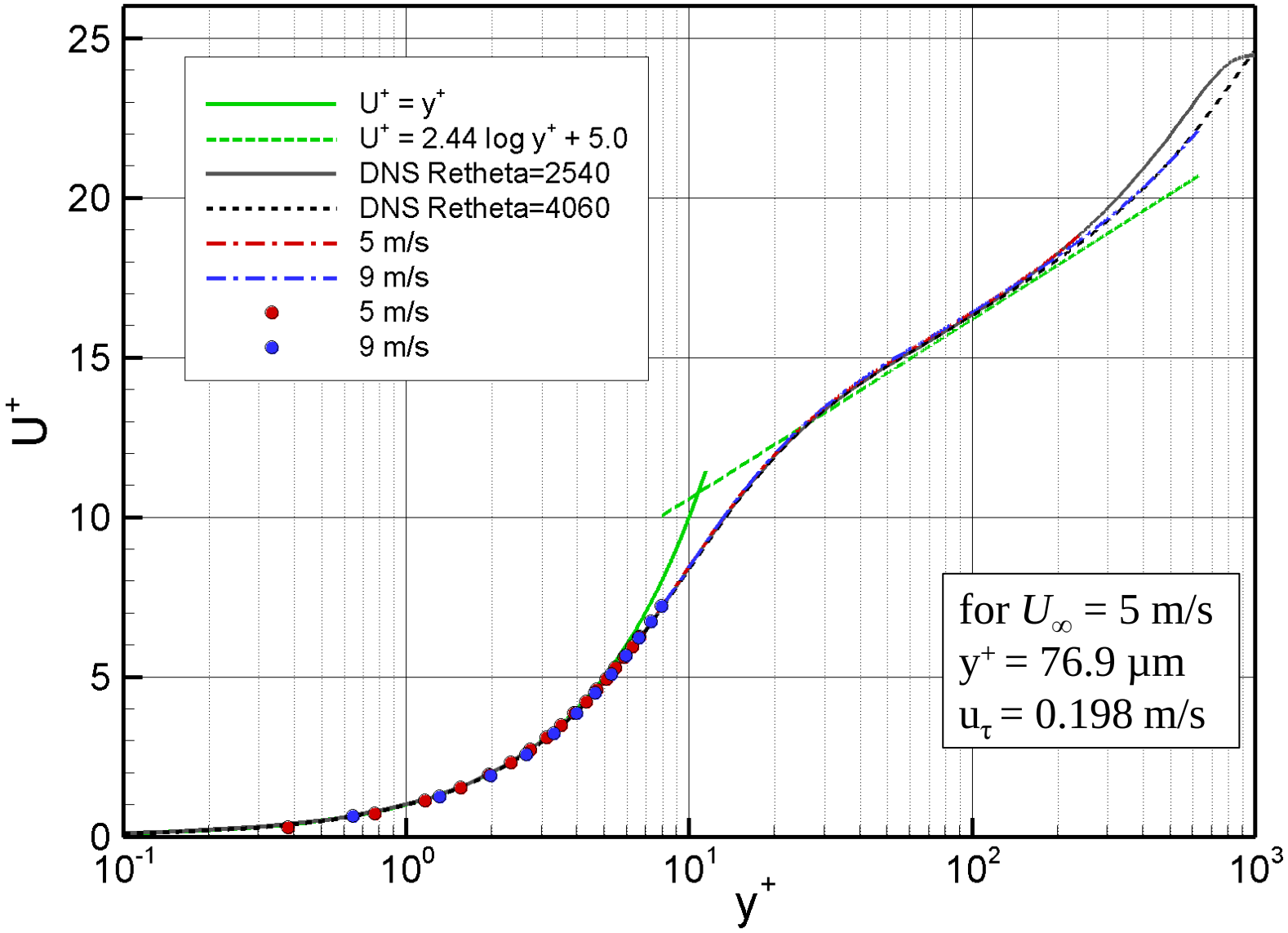




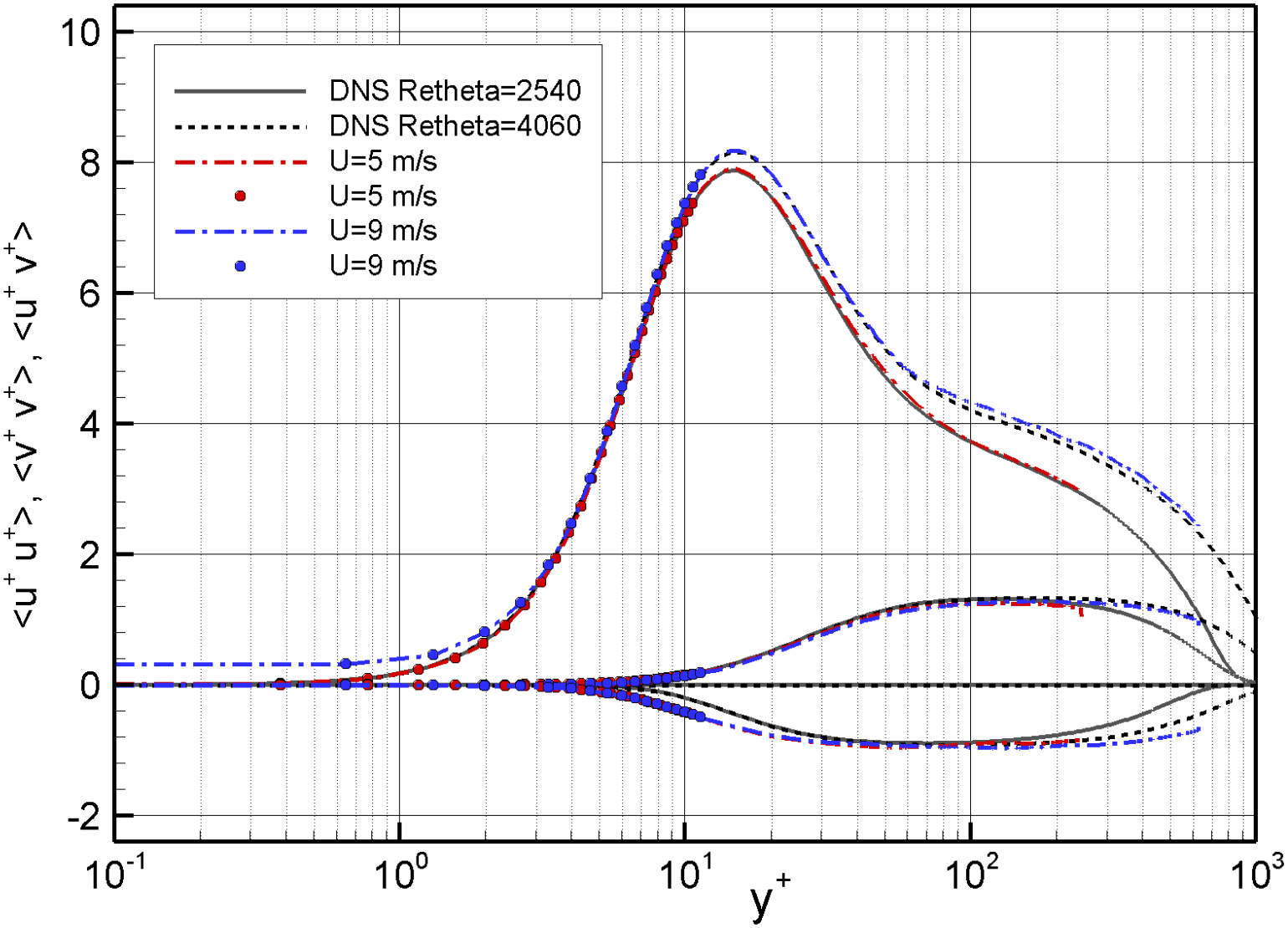
Wall



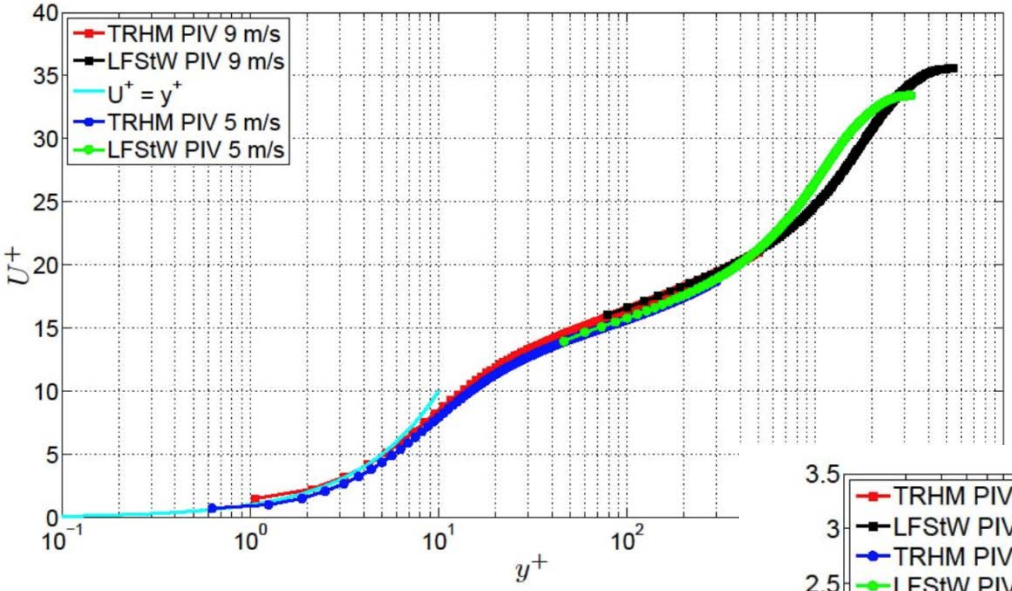
Mean velocity profiles upstream of model

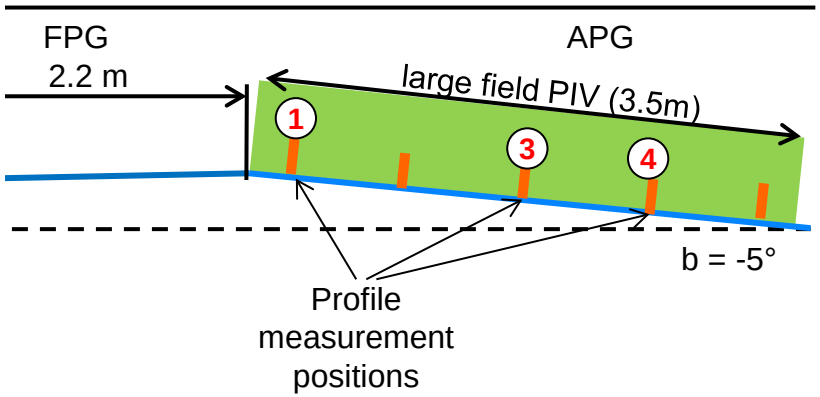


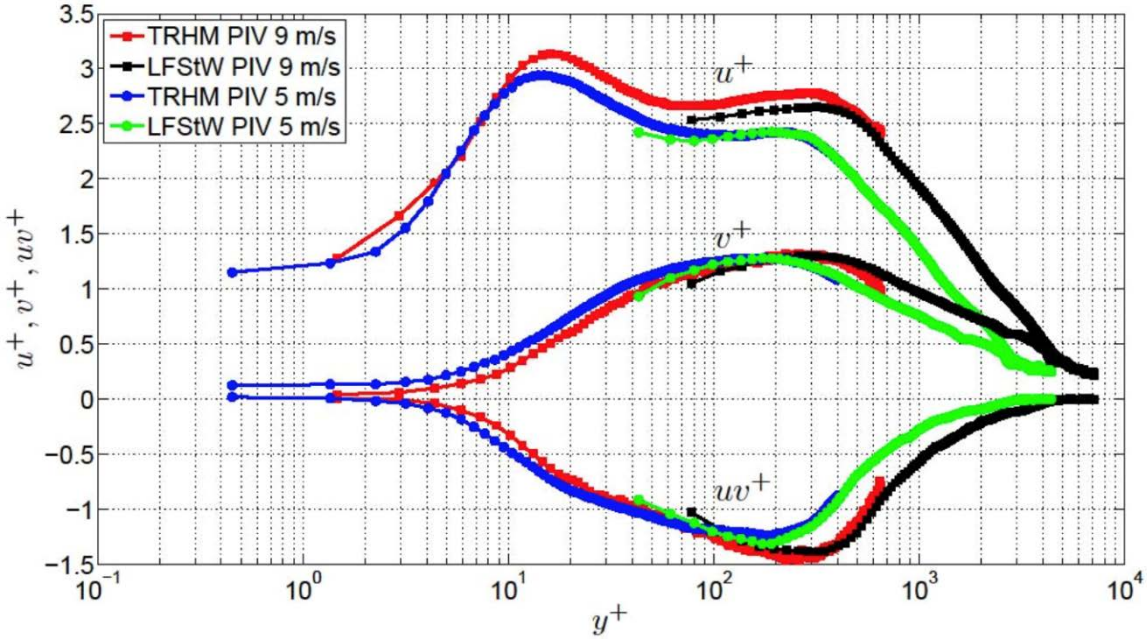
Reynolds Stresses upstream of model



Profile of mean and variances at Pos. 4

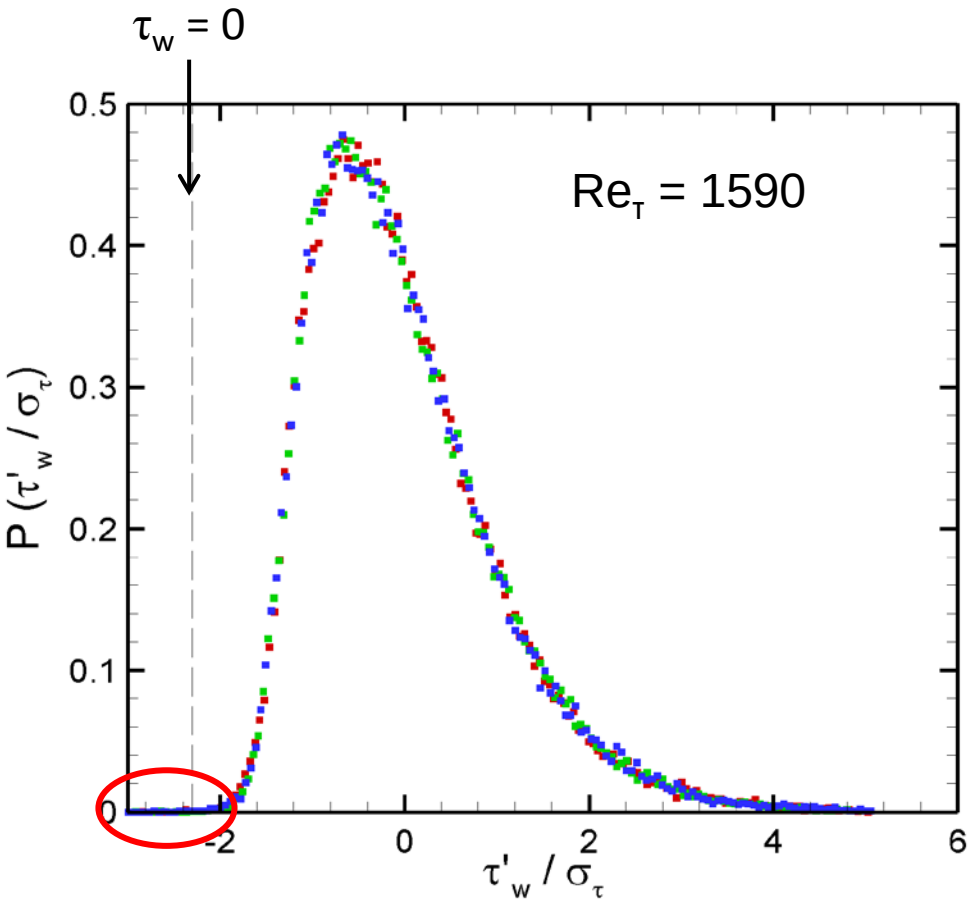




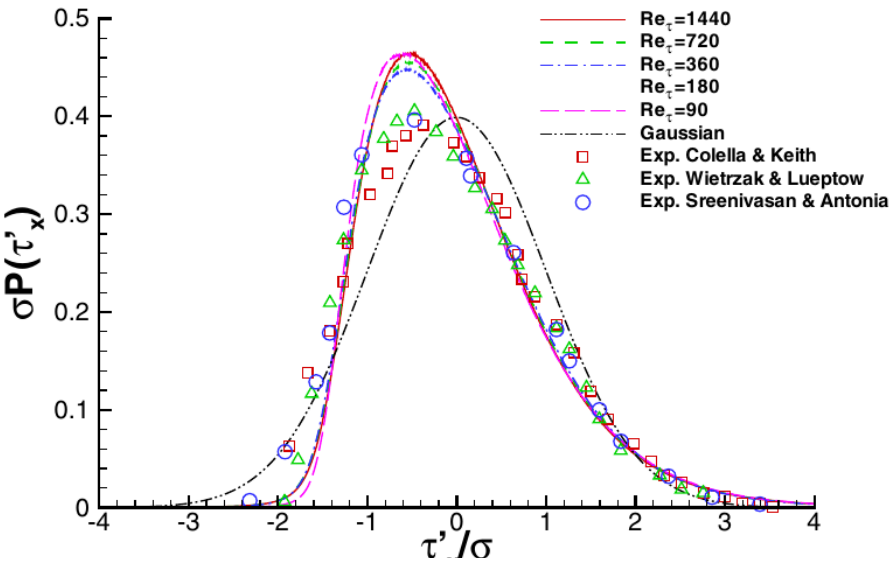


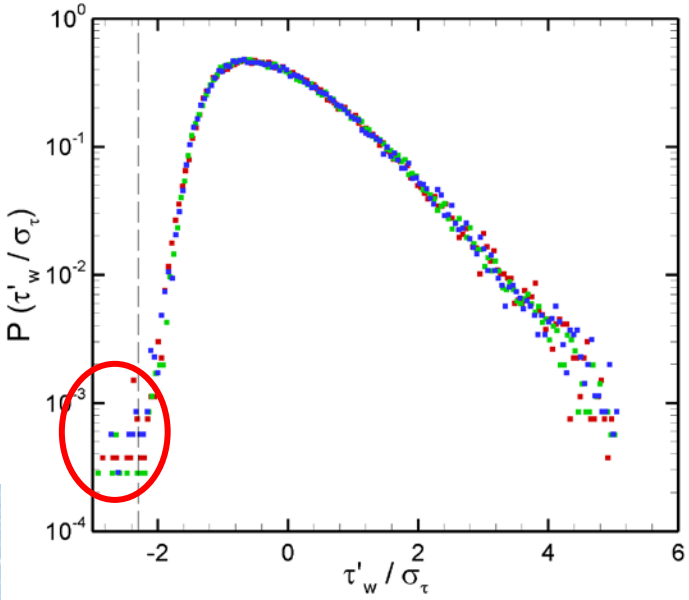
Part of material just published
J. Turbulence, Feb. 2017

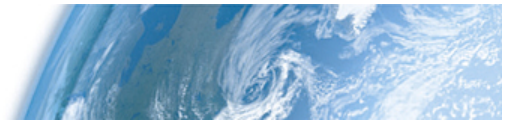
PDF of Wall-Shear Stress



Hu, Morfey & Sandham, AIAA J 44(7) 2006



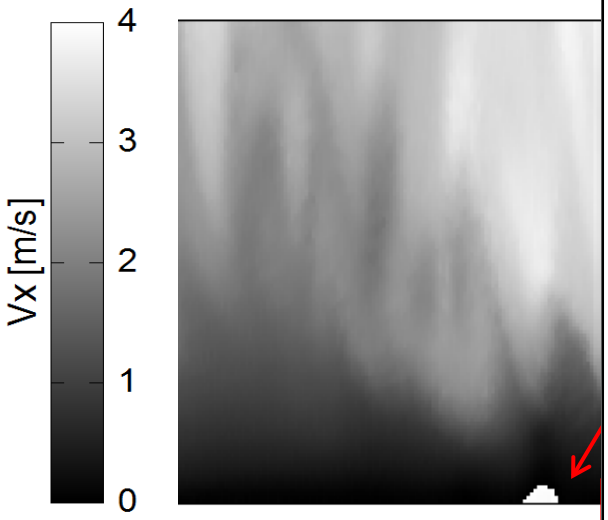




Evidence of rare back-flow events (ZPG Turb-BL)

Time-trace o
(5000 s

Time ⟹



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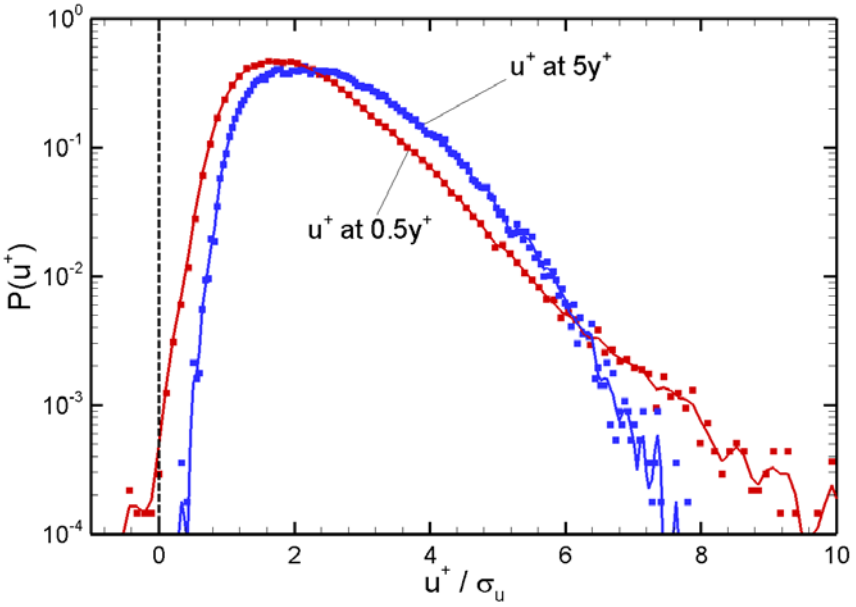
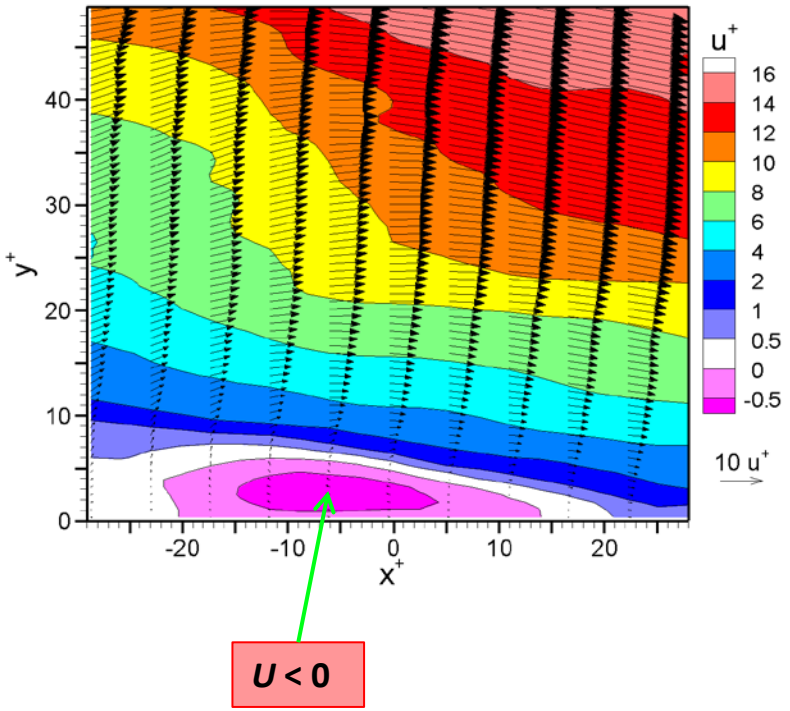
Evidence of rare back-flow events





Probability density functions of streamwise velocity u^+ at wall distances of $0.5y^+$ and $5y^+$ (Re_τ = 1070, U_∞= 5m/s)

Good agreement with DNS reported in:
Lenaers, P., Li, Q., Brethouwer, G., Schlatter, P., Örlü, R. (2012): Rare backflow and extreme wall-normal velocity fluctuations in near-wall turbulence. Phys. Fluids **24**, 035110

Events ~5-10x more frequent in APG region (detailed investigation pending)

APS Abstract G32.00004

Time resolved, near wall PIV measurements in a high Reynolds number turbulent pipe flow

C. Willert, J. Klinner
DLR Institute of Propulsion Technology, Köln (GERMANY)

J. Soria, O. Amili, M. Eisfleder
Monash University, Melbourne (AUSTRALIA)

M. Stanislas, C. Cuvier
Laboratoire de Mécanique de Lille, CNRS (FRANCE)

N. Graf
Innolas Laser GmbH, Munich (GERMANY)

G. Bellani, T. Fiorini, A. Talamelli
CICLoPE, Univ. Bologna, Predappio (ITALY)

EuHIT

DLR

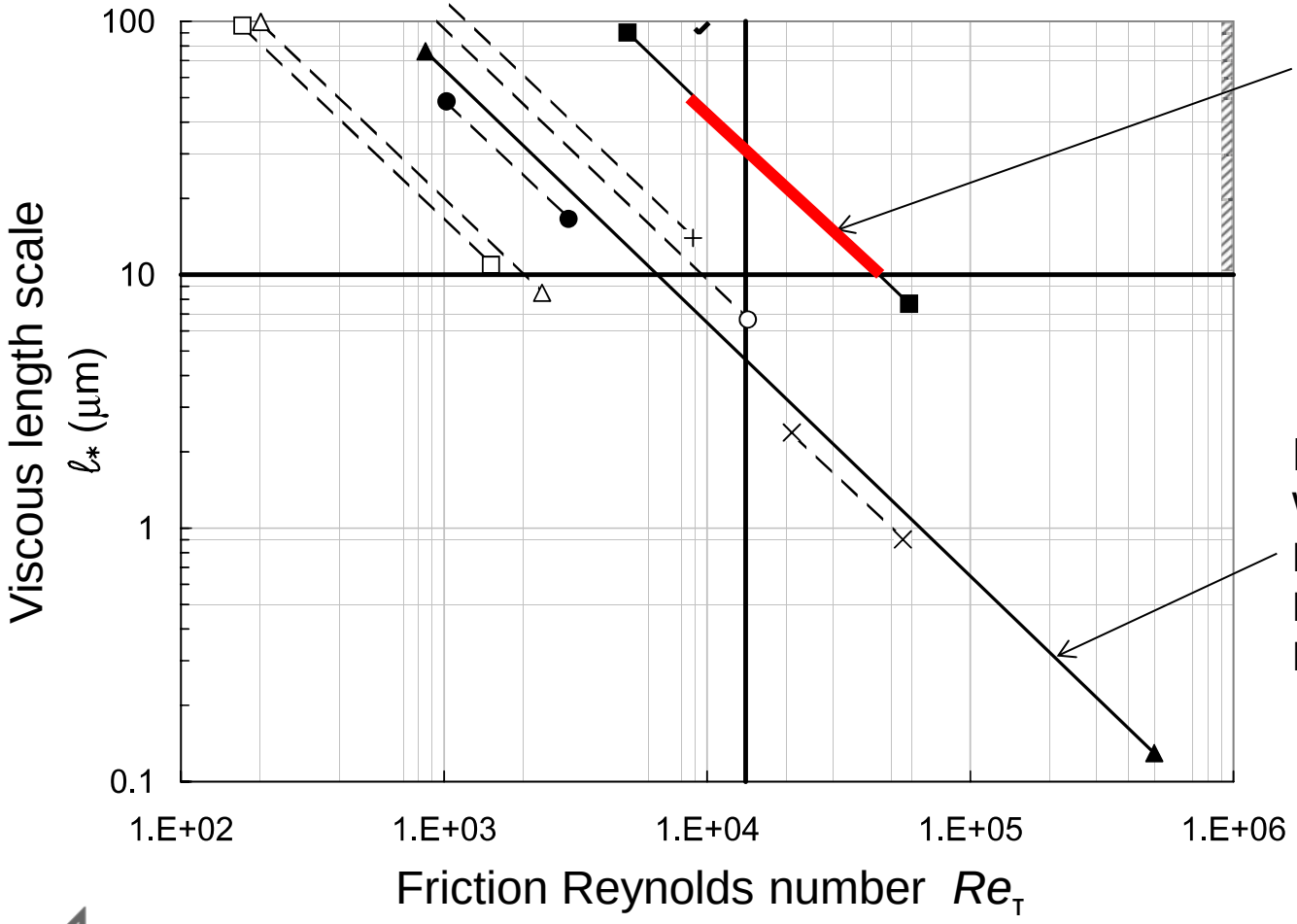
Motivation

- near wall flow structure of pipe flow so far has not been characterized well quantitatively through measurements, mainly due to finite size of probes
- for high-Re hotwire data is only available for wall distances $y > 20^+$ (e.g. *SuperPipe* Princeton)
- DNS only available at low Reynolds numbers
  for pipe flows $Re_{\tau,max} \leq 1050$ (Satake *et al,* HPC*,* 2000),
  for channel flow $Re_{\tau,max} = 5200$ (Lee & Moser*,* JFM, 2015)
- DNS difficult to perform using spectral methods due to singularity at center of pipe.
- CICLoPE pipe facility offers combination of high Reynolds number and viscous scales that can be experimentally captured → application of PIV becomes possible using standard imaging

CICLoPE = **C**enter for **I**nternational **C**ooperation in **Lo**ng **P**ipe **E**xperiments
www.ciclope.unibo.it

Reynolds number range for various pipe facilities

Talamelli et al. “CICLoPE—a response to the need for high Reynolds number experiments”, Fluid Dyn. Res. **41** (2009) 021407



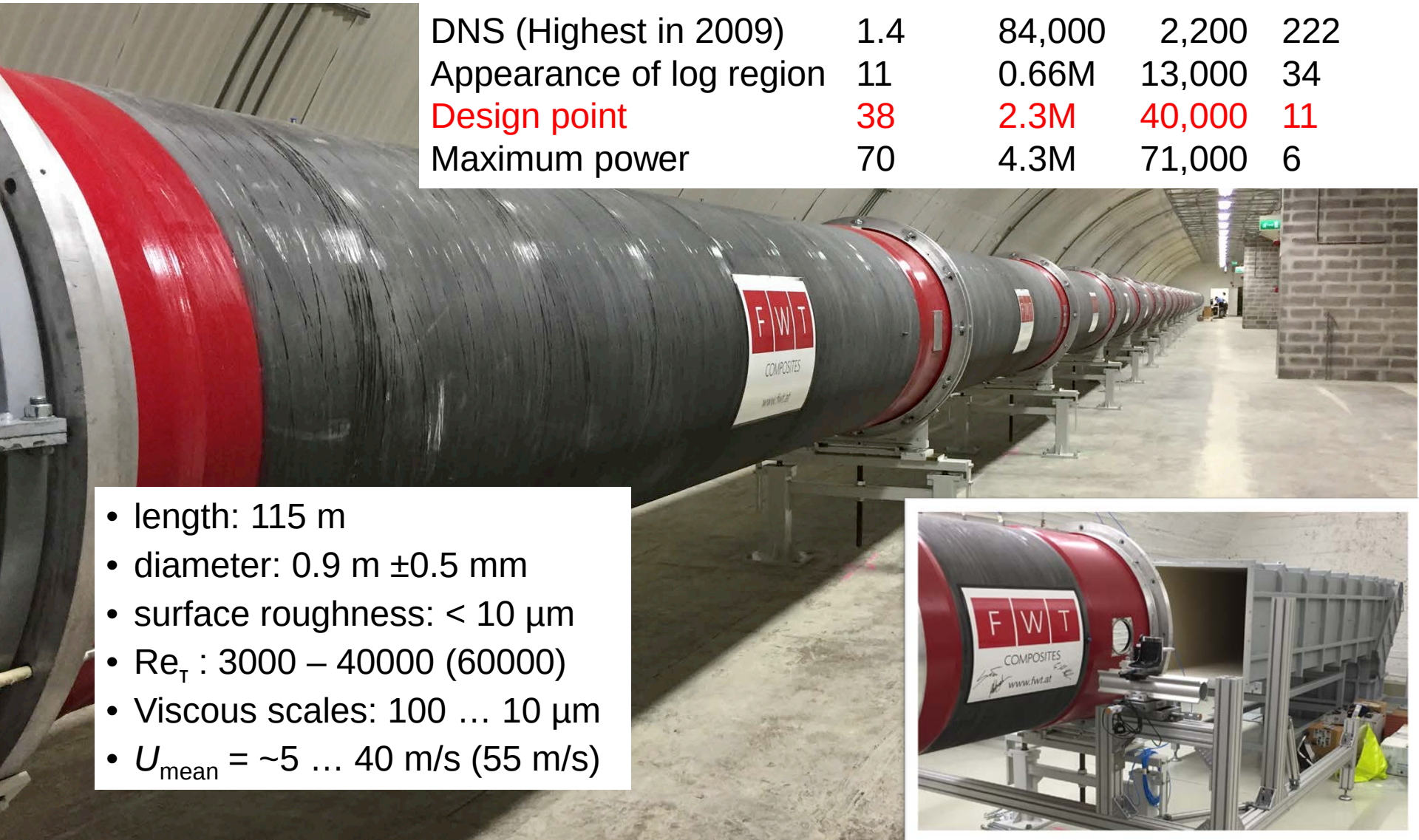
CICLoPE
Working: fluid air
Pressure: ambient
Diameter: 900 mm
Length: 110m (122D)

Princeton *Super-Pipe*
Working: fluid air
Pressure: up to 200 bar
Diameter: 129 mm
Length: 26m (202D)

CICLoPE Facility

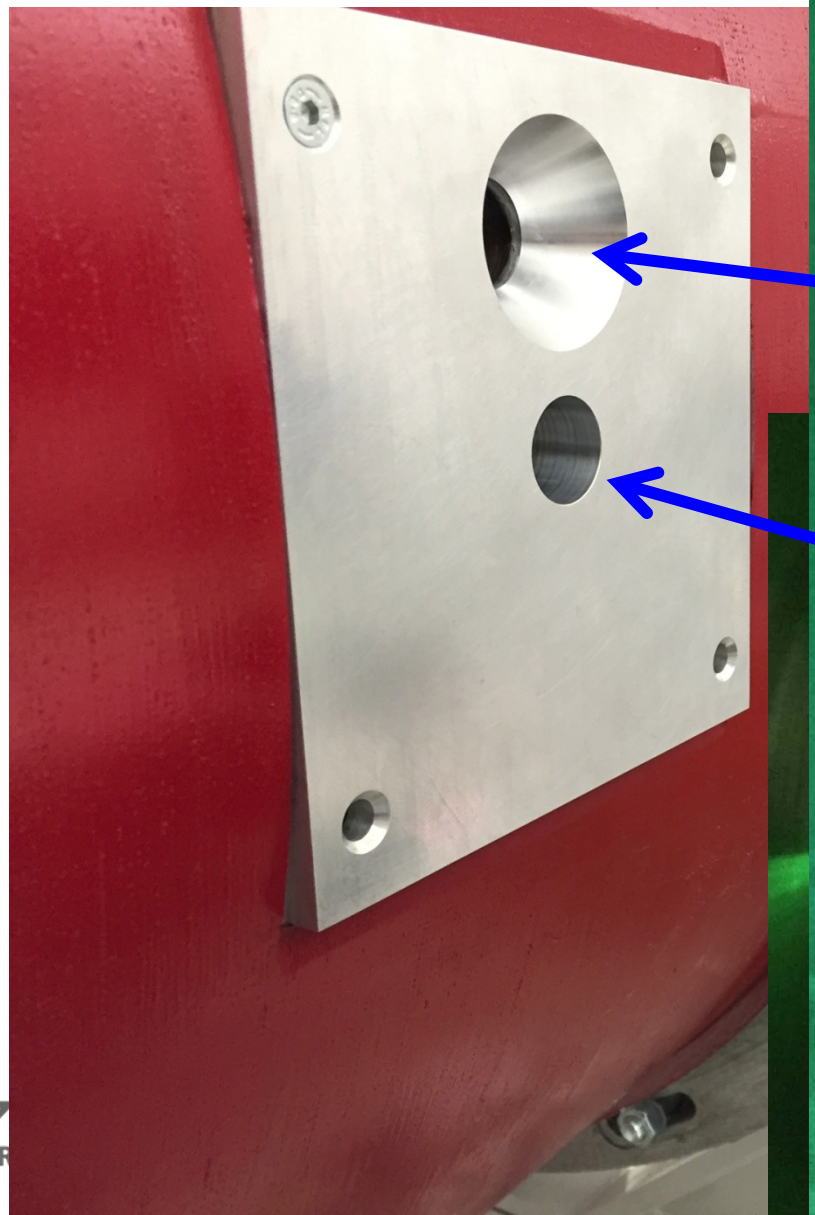
Center for International Cooperation in Long Pipe Experiments

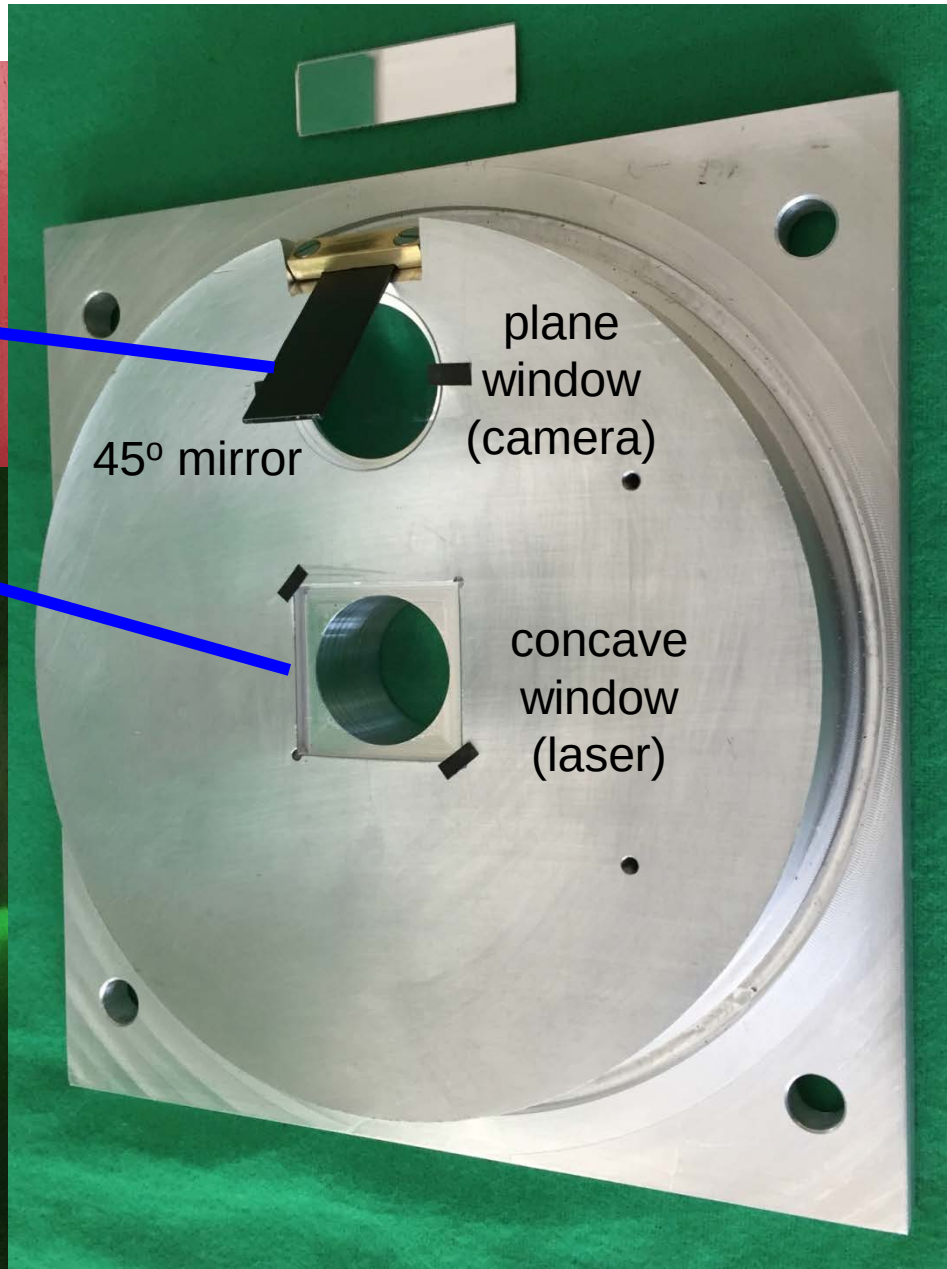
Conditions	U_m [m/s]	Re_D [-]	R^+ [-]	L^* [µm]
DNS (Highest in 2009)	1.4	84,000	2,200	222
Appearance of log region	11	0.66M	13,000	34
Design point	38	2.3M	40,000	11
Maximum power	70	4.3M	71,000	6



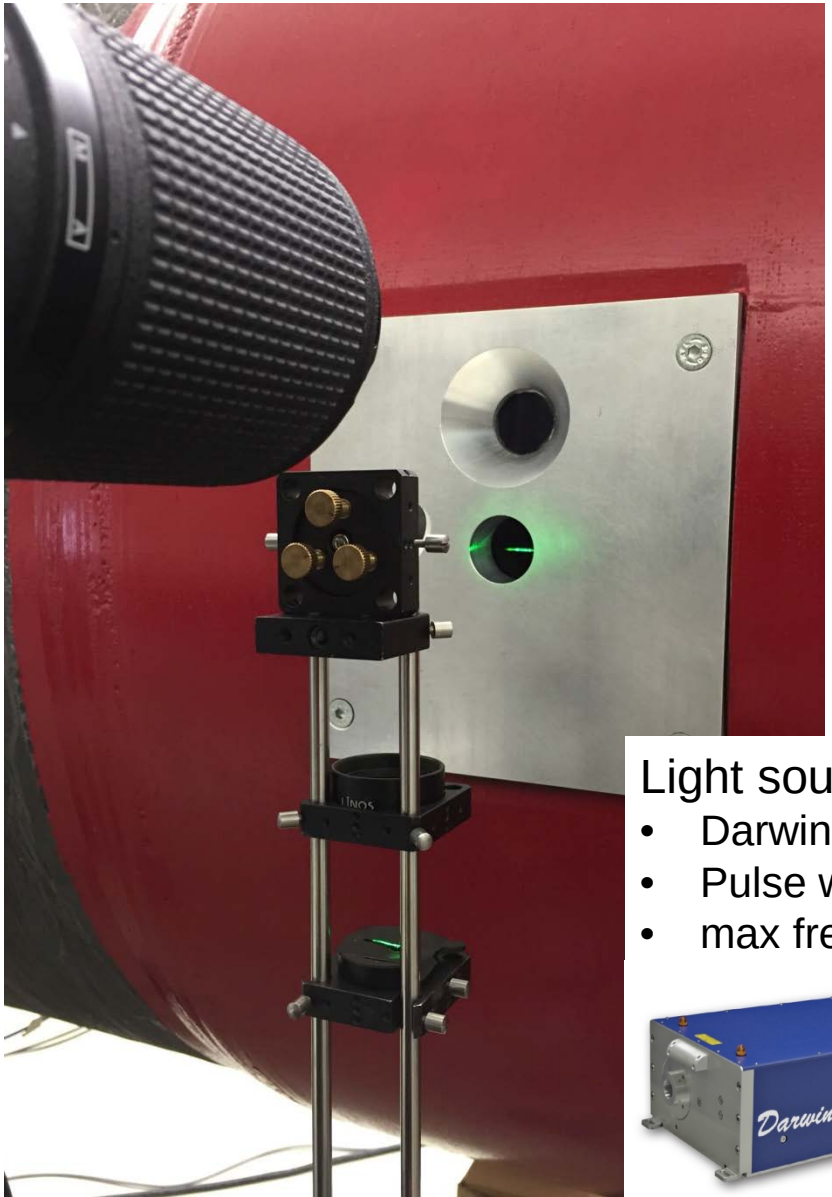
- length: 115 m
- diameter: 0.9 m ±0.5 mm
- surface roughness: < 10 µm
- Re_T : 3000 – 40000 (60000)
- Viscous scales: 100 … 10 µm
- U_{mean} = ~5 … 40 m/s (55 m/s)

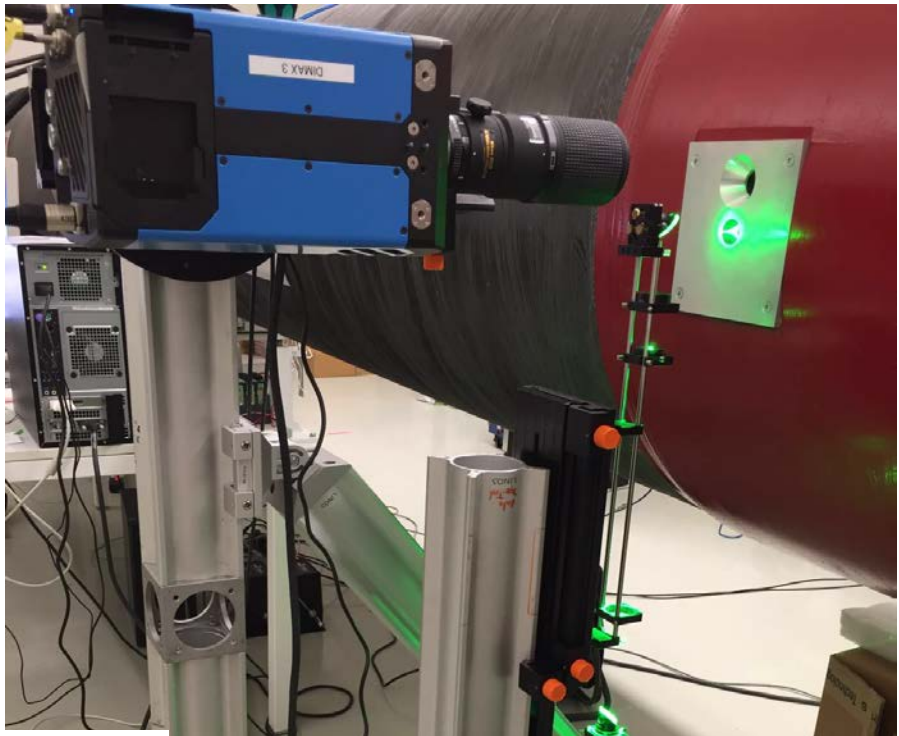
Measurement insert





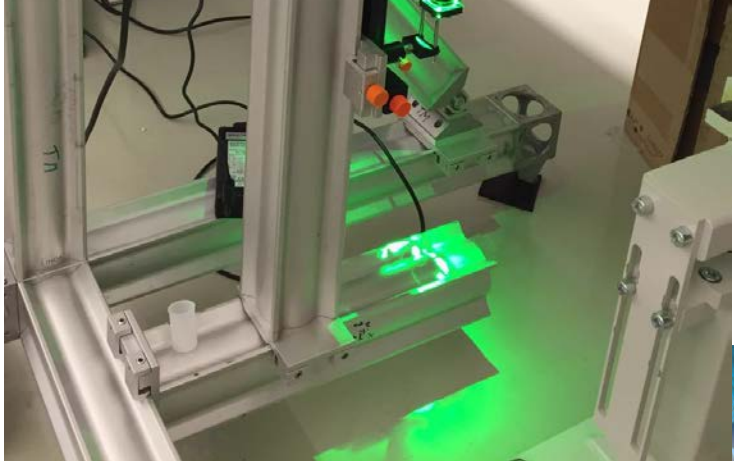
Setup for near-wall PIV measurements





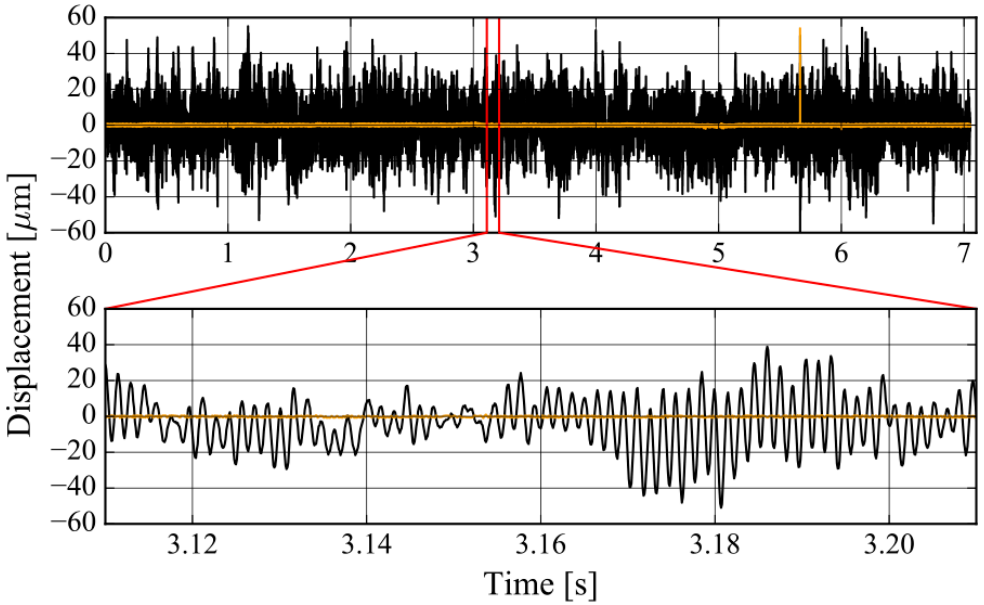
Light source:

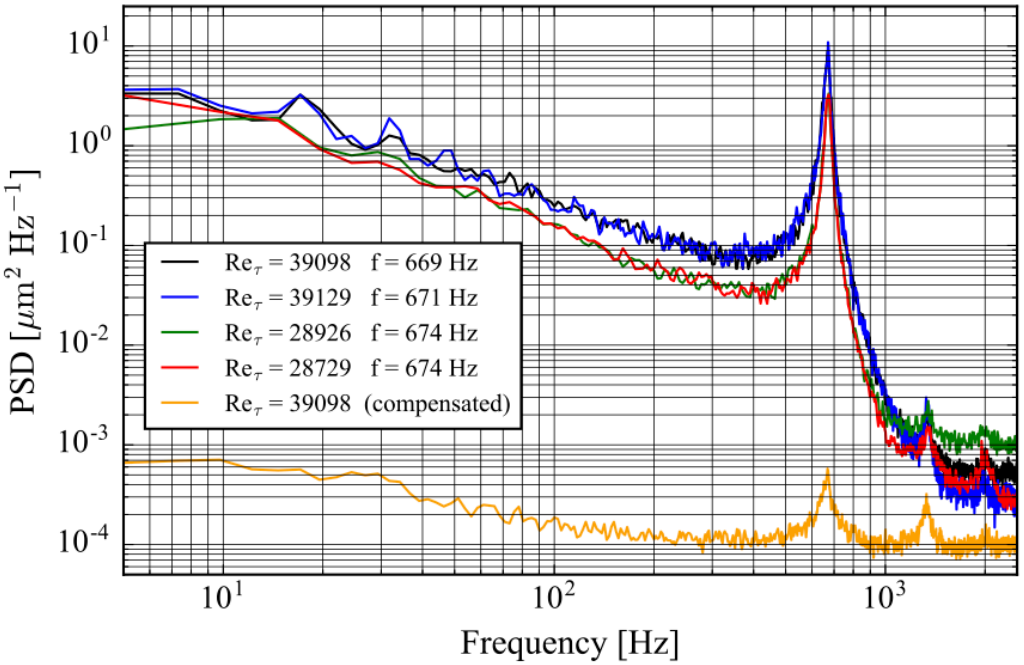
- Darwin Duo (2x40W)
- Pulse width ~300ns
- max freq. 10 kHz



Facility vibrations

- present at U ≥ 30 m/s
- structural vibration (carbon/aluminum tube)
- tracked using correlation approach
- image shifting prior to PIV analysis

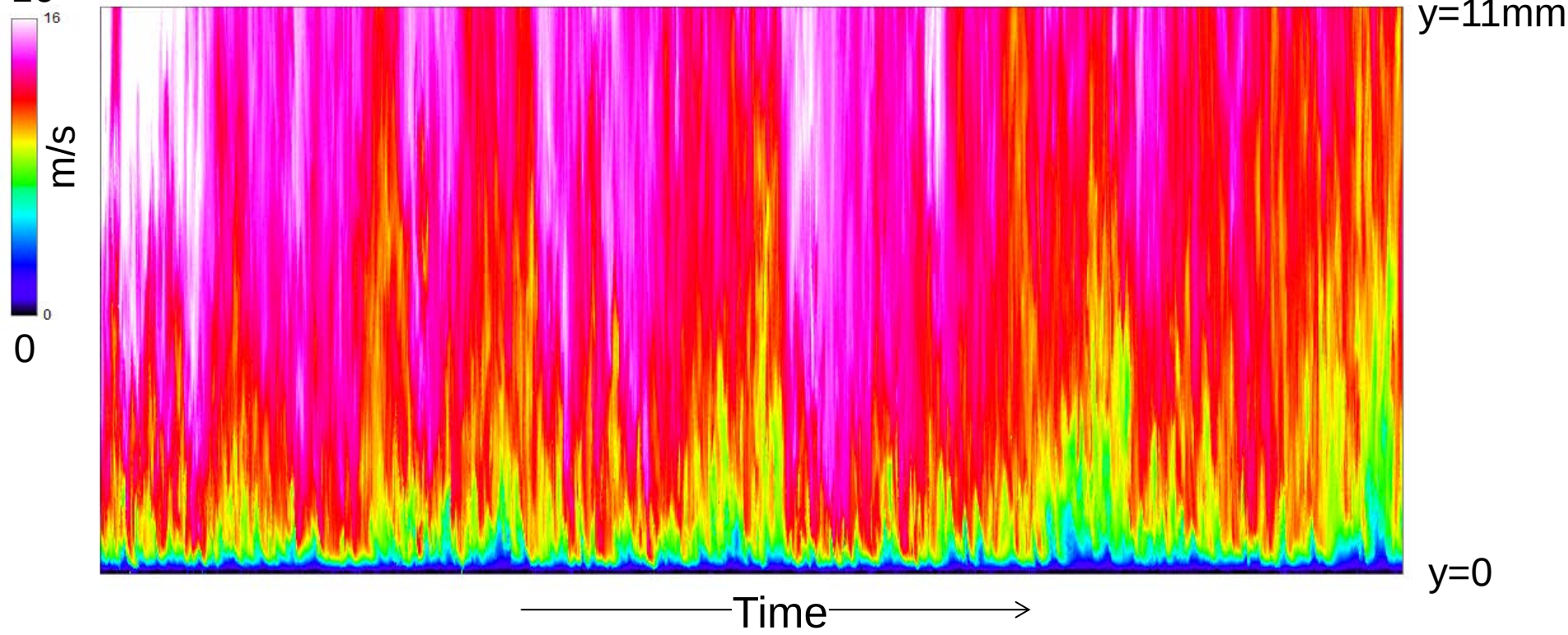




Time-record of stream-wise velocity profile

Re_τ = 20,000

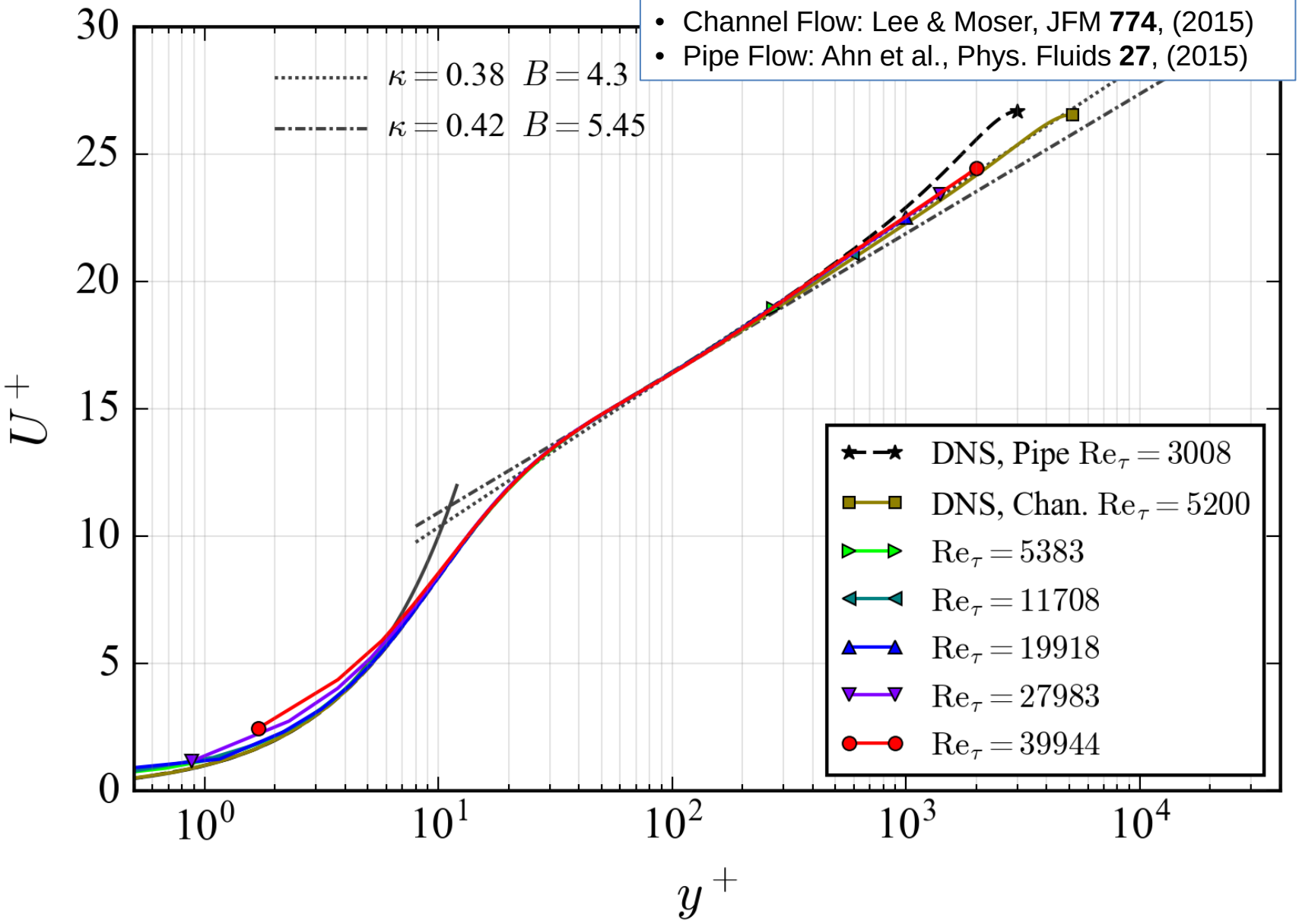
U_o = 22 m/s 1000 of 70000 samples 10 kHz sample rate



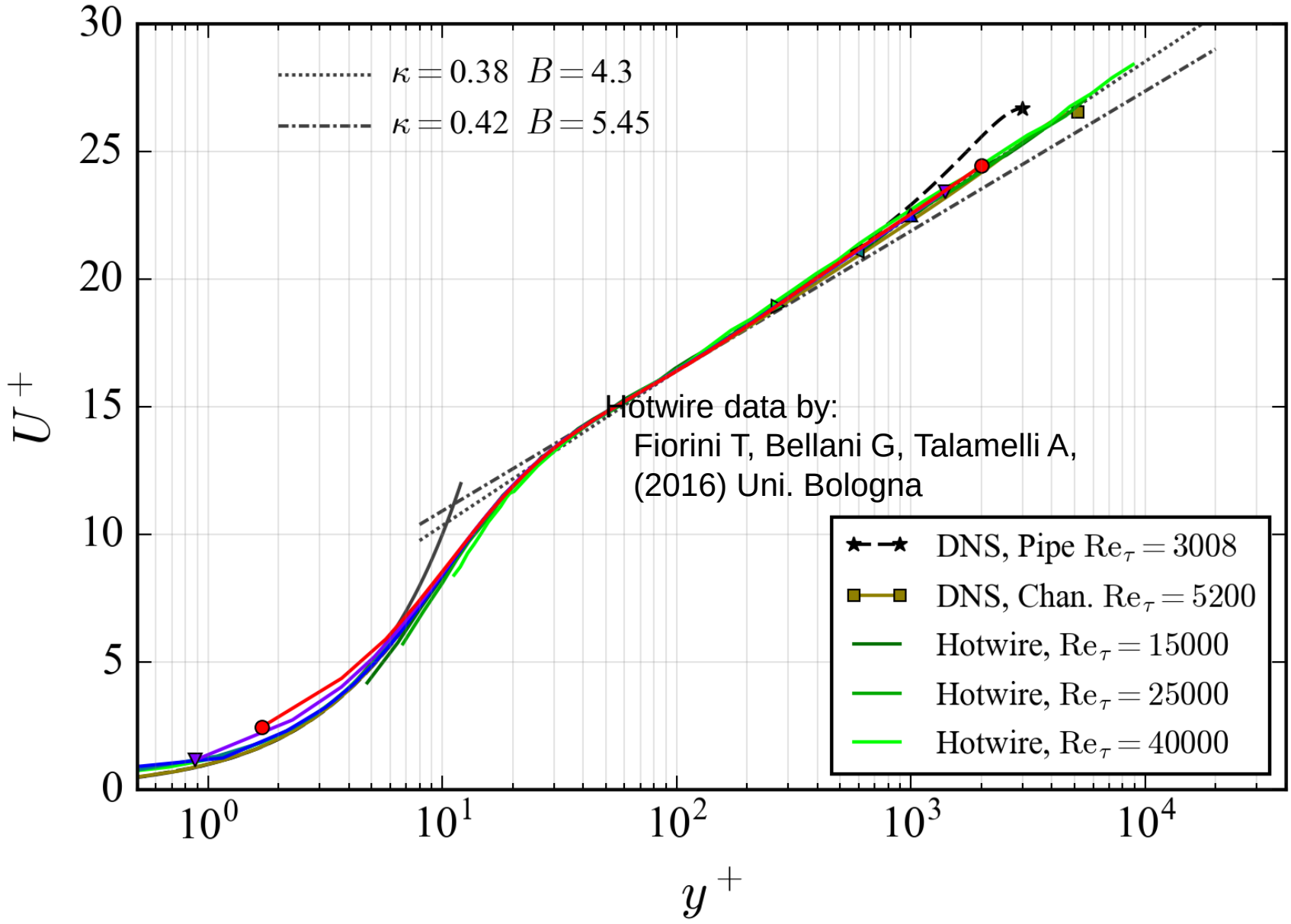
also have wall-normal velocity component (and vorticity ω_z)

Mean velocity profiles

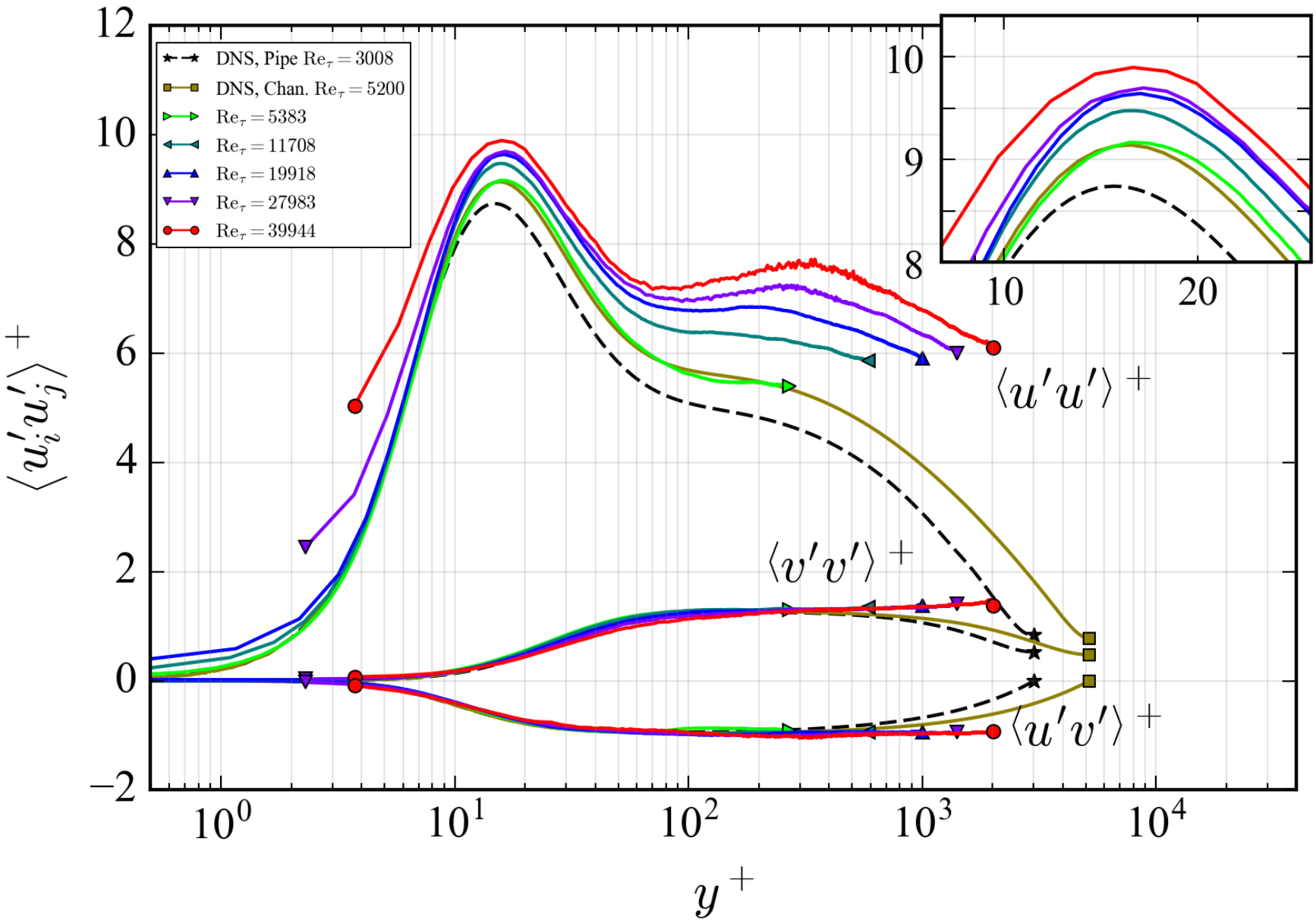
DNS data:
- Channel Flow: Lee & Moser, JFM **774**, (2015)
- Pipe Flow: Ahn et al., Phys. Fluids **27**, (2015)



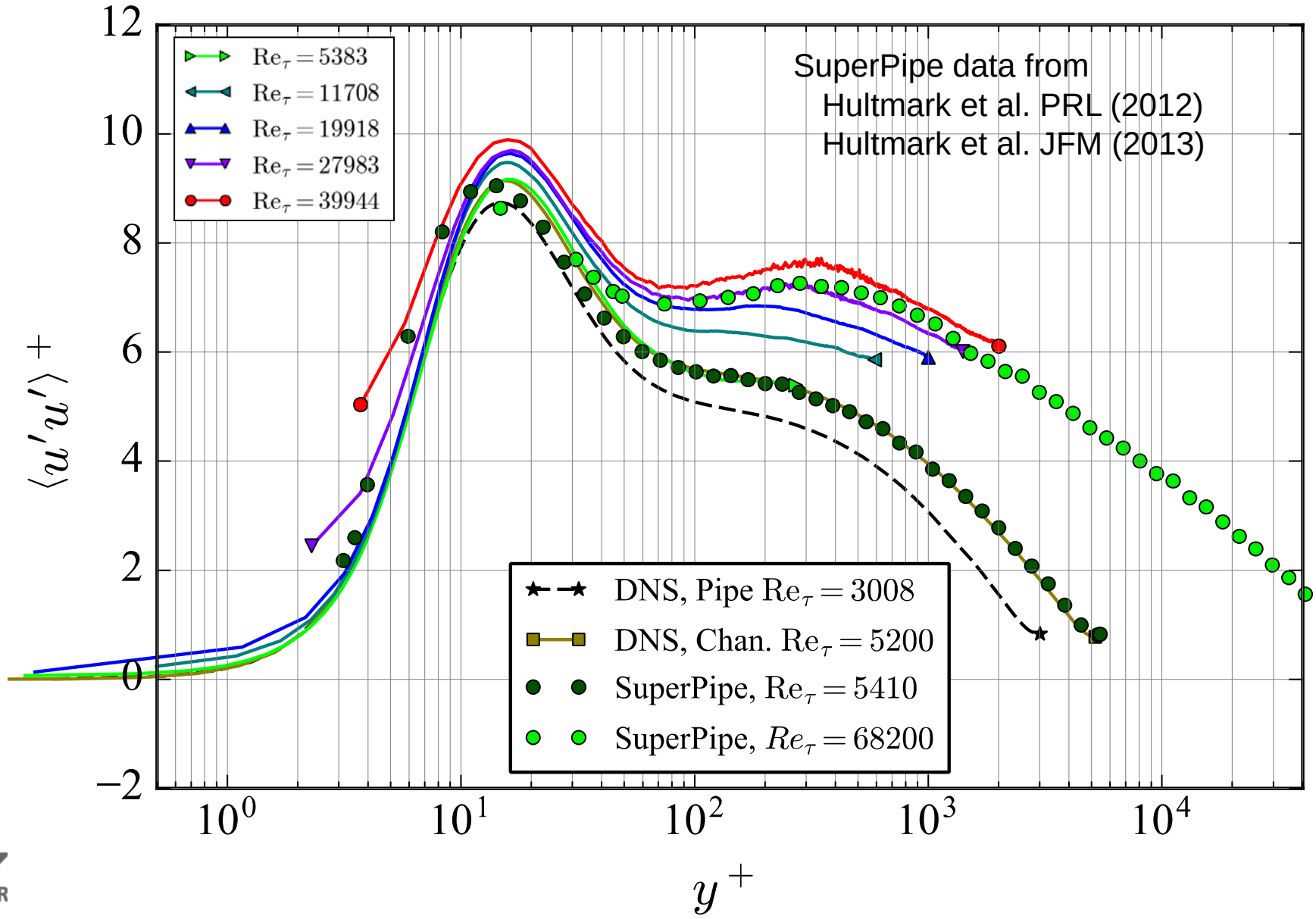
Mean velocity profiles – incl. hotwire data



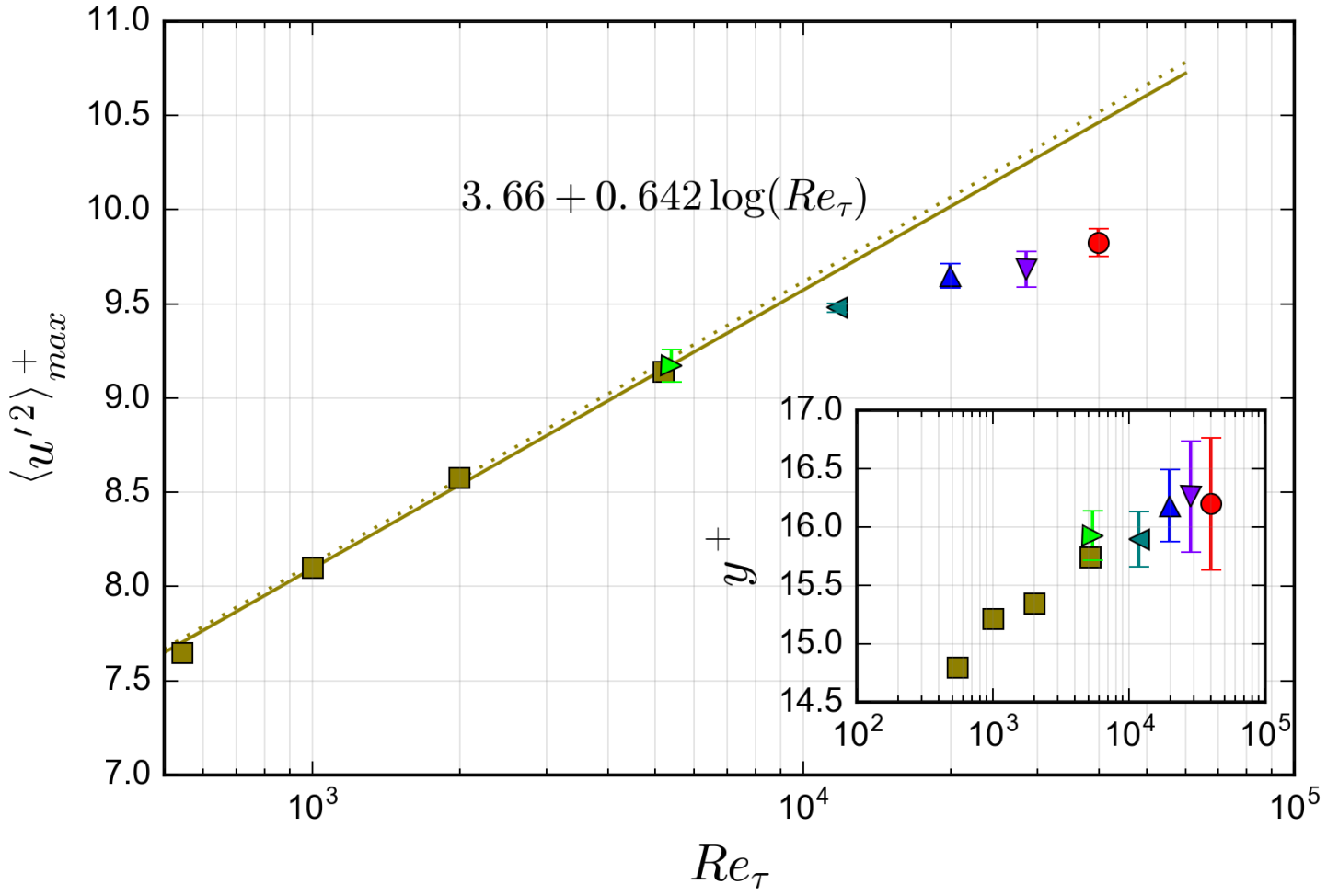
Reynolds stress profiles



Reynolds stress profiles, incl. SuperPipe data

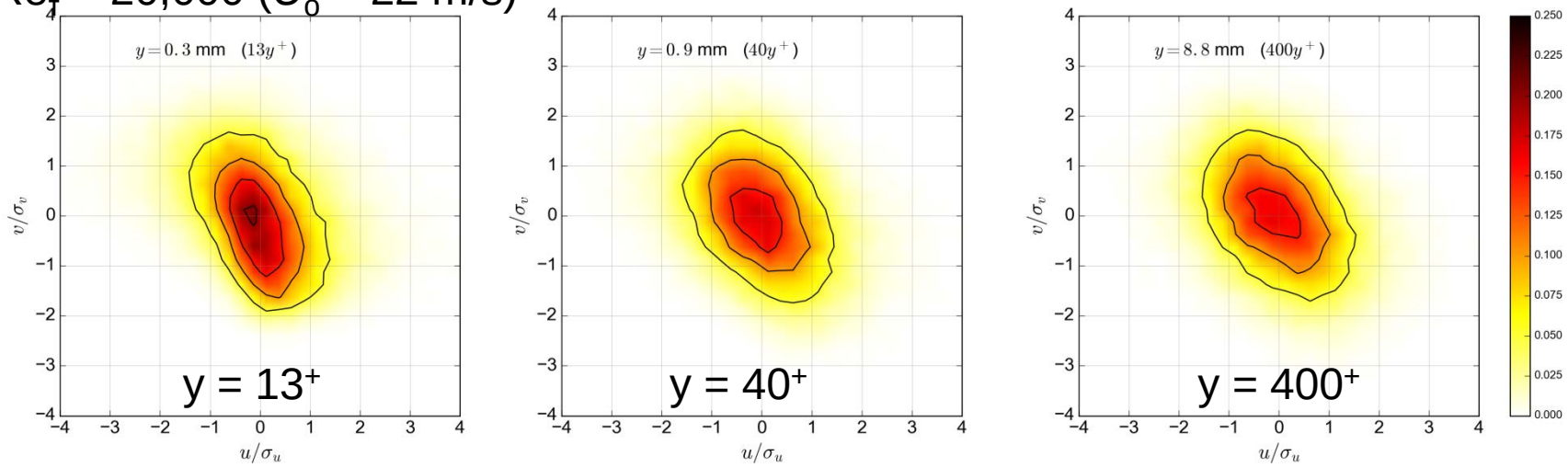


Dependence of maximum of variance *u* on Reynolds number and wall-normal location of maximum

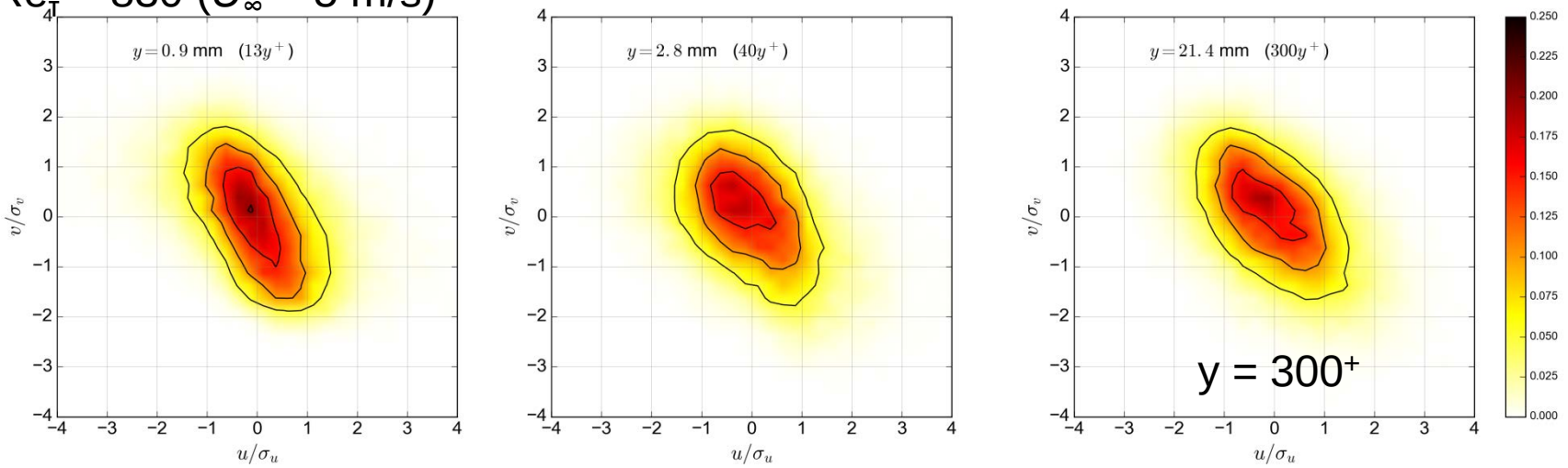


Joint-PDFs : Pipe vs. Flat Plate Turbulent BL

Re_τ = 20,000 (U_o = 22 m/s)



Re_τ = 830 (U_∞ = 5 m/s)



Summary – High-*Re* turbulent pipe flow measurements

- first application of PIV in new pipe flow facility CICLoPE (in operation since 2015)
- PIV measurements at Reynolds number range Re_T = 5,000 … 40,000
- imaging with spatial resolution of O(10µm) → resolves viscous sublayer
- statistical convergence through multiple time-records of up to 70,000 samples each
- inner peak grows with Re_T (behaviour very similar to ZPG-Turb. BL)

- work in progress:
  - extract unsteady wall-shear stress from images (comparison with dP-based estimates)
  - reprocess using PTV methods (STB) to get max. spatial resolution,…
  - …